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Research

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Effect of CFRP on the Buckling Behavior of Thin-Walled Steel Cylindrical Shells under Local Support Settlement

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ABSTRACT

Thin-walled shells are among the most important components of industrial structures such as liquid storage tanks, silos, pressurized pipes, and similar systems. These structures have very small wall thickness compared with their other dimensions and are therefore classified as thin-walled shells. In this study, thin-walled cylindrical steel shells strengthened with carbon fiber–reinforced polymer (CFRP) are modeled under local support settlement using the finite element software ABAQUS, and their stress state, buckling load, and radial and vertical deformations are investigated. The results show that CFRP-strengthened shells have higher buckling capacity than unstrengthened shells, and that this capacity increases with the number of CFRP layers and the shell thickness. In addition, strengthening the shell reduces its deformations and displacements.

Keywords: cylindrical shell, local settlement, thin-walled, CFRP, buckling

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1. INTRODUCTION

One of the main types of equipment widely used in industrial plants and facilities is steel tanks, which are employed for storing and retaining materials and fluids. Foundation settlement is one of the key causes of failure in such tanks. Support settlement under the tank wall can be classified into three components: uniform settlement, tilt (differential) settlement, and local settlement. Among these, local settlement has the greatest influence on tank behavior and can lead to large displacements, shell buckling, and ultimately tank failure.

In the present study, the effect of CFRP on the buckling behavior of thin-walled steel cylindrical shells subjected to local support settlement is investigated.

Godoy and Sosa (2003) examined the influence of support settlements on the out-of-plane displacements of thin-walled cylindrical storage tanks with fixed roofs [1]. In 2005, Holst and Rotter studied the buckling behavior of a thin cylindrical shell under axial compression in the region of a local settlement [2]. In 2009, Batikha et al. proposed a new method for strengthening cylindrical shells against

elephant's-foot buckling using FRP composites. They showed that using a relatively small amount of FRP in the critical region can effectively solve the problem and increase buckling strength. The strengthened shell was analyzed using linear elastic bending theory [3].

Cao and Zhao (2010) numerically investigated the buckling behavior of fixed-roof cylindrical steel storage tanks under harmonic settlement. They studied the effect of the number of harmonic waves (n), the radius-to-thickness ratio (r/t), the height-to-radius ratio (h/r), and geometric imperfection amplitude (d_0/t) on the buckling resistance of storage tanks [4].

In 2013, the effect of top stiffening rings on the critical harmonic settlement of open-top tanks was examined by Gong et al. Their results indicated that the critical harmonic settlement for a tank with a stiffening ring is smaller than that of a tank without a stiffener [5].

Fahmy and Khalil (2016) investigated the influence of wall thickness variation on the buckling mode of tank walls subjected to critical harmonic settlement in open-top tanks. The study was conducted on four tanks with identical geometry and material properties except for the wall thickness. For each tank, several harmonic settlement waves of equal amplitude were applied, and the buckling modes and critical vertical settlements were compared [6].

In 2017, Gong et al. provided recommendations regarding the harmonic components that must be considered when decomposing measured settlements into harmonic components using Fourier series. They also discussed the effects of the considered harmonic components on the buckling behavior of tanks with floating and conical roofs [7].

Fan et al. (2018) studied the buckling behavior of tanks with conical roofs under harmonic settlement. Their results showed that when the settlement

reaches a critical value, the tank wall undergoes a sudden jump in deformation. This implies that, in comparison with the conical roof, the tank wall is more vulnerable to buckling [8].

Maali et al. (2019) tested thin-walled cylindrical shells, with and without CFRP, under external pressure with different dent depths and orientations [9]. In the same year, Taraghi et al. conducted an experimental study on the behavior of conical steel shells strengthened with CFRP laminates under uniform external pressure and concluded that CFRP sheets significantly increase shell stiffness and buckling resistance [10].

In 2020, Nassernia and Showkati carried out an experimental investigation on local settlement in steel cylindrical tanks with constant and variable wall thickness. The tanks were first modeled using the finite element method, then fabricated in the laboratory and subjected to local support settlement along the bottom edge. Settlement values, buckling load, ultimate load, and radial deformations were compared [11].

Also in 2020, Bohra and Guzey proposed a method for evaluating the mechanical integrity (fitness-for-service) of open-top cylindrical storage tanks subjected to differential settlement [12].

Naseri et al. (2021) experimentally evaluated the geometrical and physical behavior of thin-walled steel tanks subjected to local support settlement. They investigated the influence of the height-to-radius ratio (L/R) and the ratio of settlement width to tank circumference (S), as well as the effect of a top stiffening ring on tank behavior [13].

In 2022, Krishna et al. studied the buckling behavior of FRP-strengthened cylindrical metallic shells with various geometric imperfections and central cut-outs with and without reinforcement around the cut-out [14].

2. METHODOLOGY

The specimens were modeled using the finite element software ABAQUS. The cylindrical shells have a diameter of 1000 mm and a height of 500 mm. The stiffener used in these specimens is an angle section with dimensions $4 \times 30 \times 30$ mm. The steel cylindrical wall and the CFRP material were both modeled using S4R shell elements. The connection between the stiffener and the shell was modeled using a Tie constraint.

The modulus of elasticity and Poisson's ratio of the steel material were taken as 230 GPa and 0.3, respectively. The mechanical properties of the composite CFRP material, including elastic moduli, Poisson's ratios, and shear moduli in the longitudinal direction (local direction 1) and transverse directions (local directions 2 and 3), were defined in the software according to Table 1. To assess the CFRP behavior, the Hashin failure

criterion was adopted, considering four failure modes: fiber tension, fiber compression, matrix tension, and matrix compression [15]. The CFRP was modeled as a unidirectional lamina with a

thickness of 0.17 mm. In all specimens, the fiber orientation was taken as 90° , and the settlement angle was 30° . Details of the modeled specimens are given in Table 2.

Table 1. Mechanical properties of CFRP composite material

Parameter	Value
V12	0.32
E1 (GPa)	240
E2 (GPa)	17
G12 (GPa)	4.5
G13 (GPa)	4.5
G23 (GPa)	2.5

Table 2. Details of modeled specimens

Specimen	Shell thickness (mm)	Number of CFRP layers
A-WF	0.3	– (without CFRP)
A-F1L	0.3	1
A-F2L	0.3	2
B-WF	0.6	– (without CFRP)
B-F1L	0.6	1
B-F2L	0.6	2

3. RESULTS AND DISCUSSION

After completing the finite element modeling, two types of analysis were performed for each specimen. The first was an eigenvalue (buckling) analysis, used to introduce geometric imperfections into the structure. A fraction of the first, second, and third buckling modes was applied as the initial geometric imperfection.

The second analysis was a nonlinear Riks analysis, which provided the stress distribution in terms of the von Mises stress and the displacements in the radial and vertical directions. Figures 1, 2, and 3 show the deformed shapes of the cylindrical shell with a thickness of 0.3 mm under local support settlement.

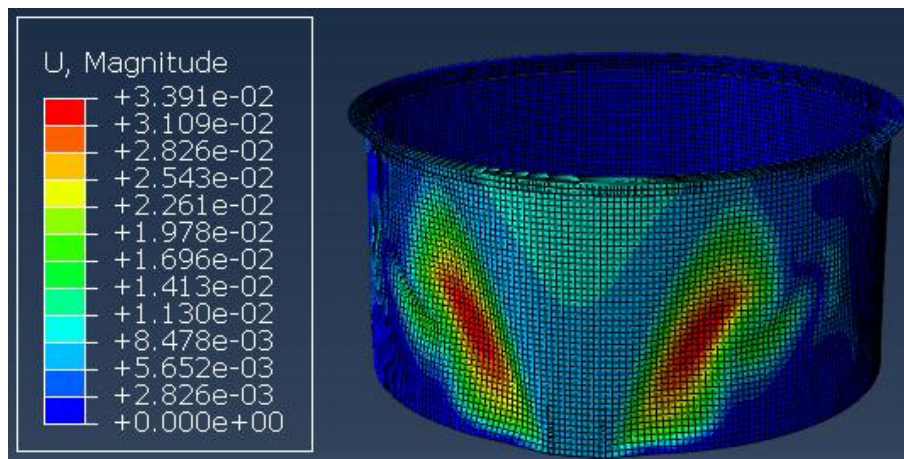


Figure 1. Deformed shape of specimen A-WF under local support settlement

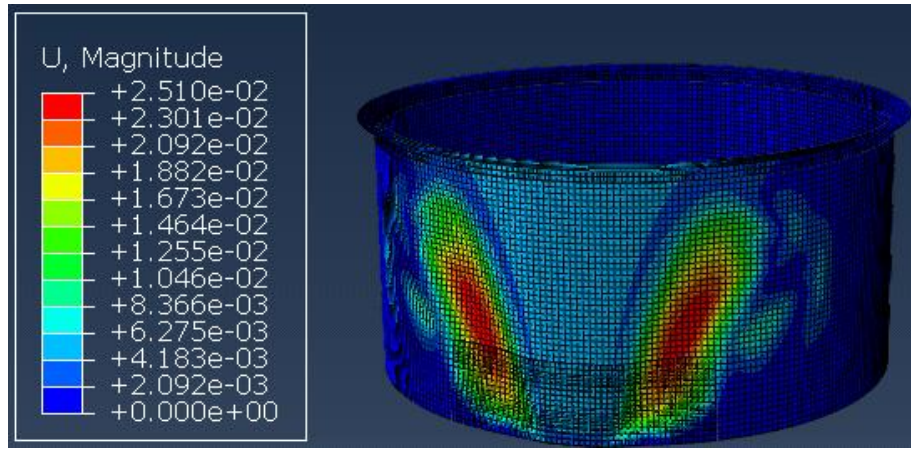


Figure 2. Deformed shape of specimen A-F1L under local support settlement

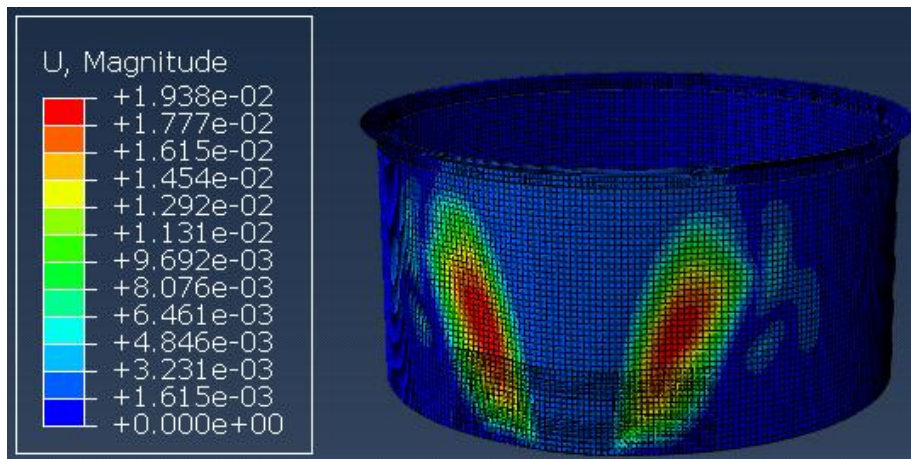


Figure 3. Deformed shape of specimen A-F2L under local support settlement

From these figures it is observed that local support settlement induces shear buckling in the tank wall of the cylindrical shells. The deformation of the specimens has a V-shaped pattern, initiating at the location of the applied settlement. By strengthening the specimens with CFRP and increasing the number

of CFRP layers, the maximum displacement caused by local settlement decreases. Moreover, the use of CFRP reduces the spatial extent of the deformed region and prevents its propagation.

The maximum displacements of the specimens in different directions are presented in [Table 3](#).

Table 3. Maximum stresses and displacements of specimens in the Riks analysis

Specimen	Max. horizontal disp. U1 (mm)	Max. vertical disp. U2 (mm)	Max. horizontal disp. U3 (mm)
A-WF	30.14	8	15.2
A-F1L	23	4.2	10.3
A-F2L	18	2.4	7.3
B-WF	74	113	86
B-F1L	70	98	81
B-F2L	20	7	15

As seen in [Table 3](#), strengthening the specimens with CFRP reduces the maximum radial and vertical displacements in all directions. With increasing shell

thickness, the maximum displacement experienced by the specimen increases and the shells are able to sustain larger deformations before failure.

3.1. Equivalent load-local settlement behavior

The following diagrams show the relationship between the applied vertical load and the imposed settlement for the specimens. The horizontal axis

represents the settlement induced in the structure (in mm), and the vertical axis represents the equivalent load corresponding to this settlement (in N).

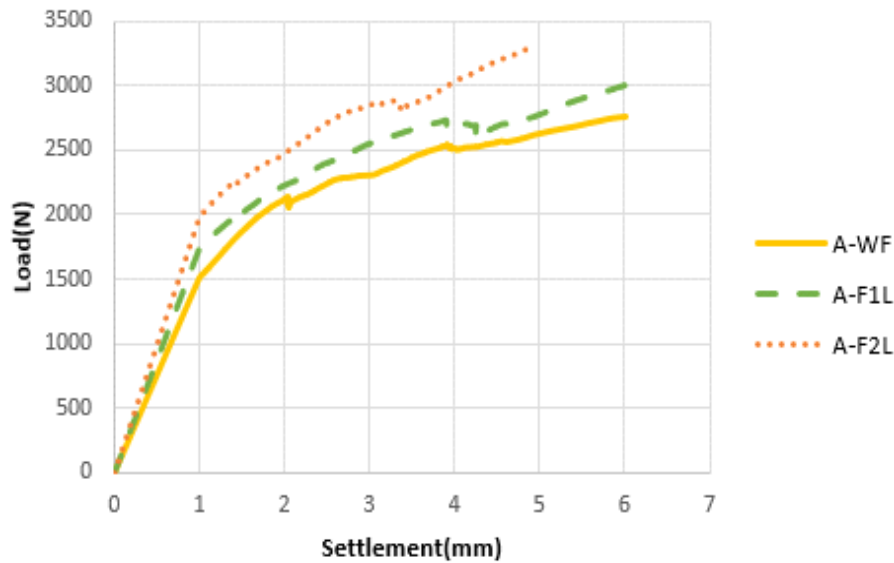


Figure 4. Vertical load–settlement curves for specimens with 0.3 mm wall thickness under local support settlement

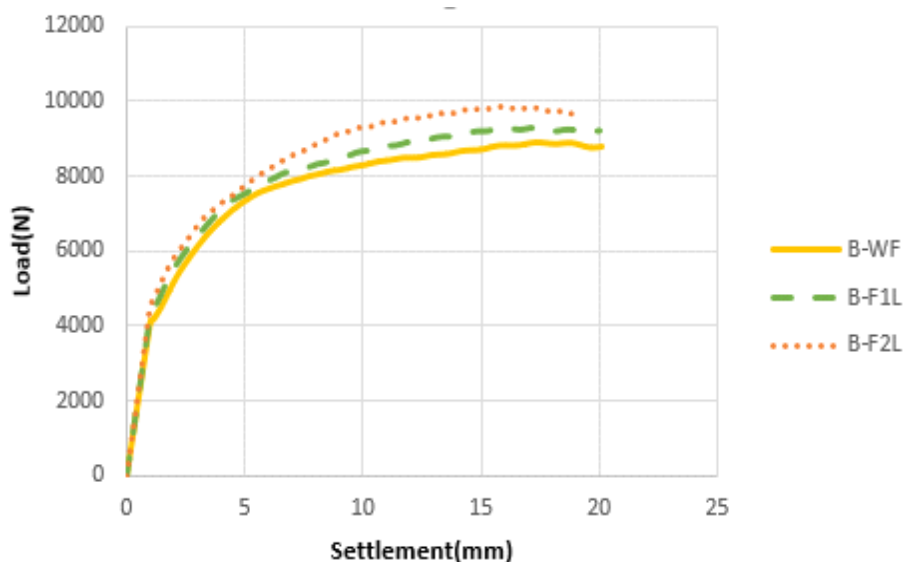


Figure 5. Vertical load–settlement curves for specimens with 0.6 mm wall thickness under local support settlement

From Figures 4 and 5 it can be observed that the maximum equivalent load in the unstrengthened specimens (without CFRP) is smaller than that of the strengthened specimens. By strengthening the specimens and increasing the number of CFRP layers, the equivalent load increases; that is, the

target settlement occurs at a higher load level in the strengthened shells. Furthermore, increasing the wall thickness leads to an increase in the equivalent load associated with a given settlement. Therefore, the use of CFRP to strengthen steel tanks is an efficient and effective method.

3.2. Radial displacement -local settlement behavior

The following diagrams illustrate the relationship between settlement and radial displacement for the specimens. The horizontal axis represents the

settlement in the structure (in mm), and the vertical axis shows the radial displacement (in mm).

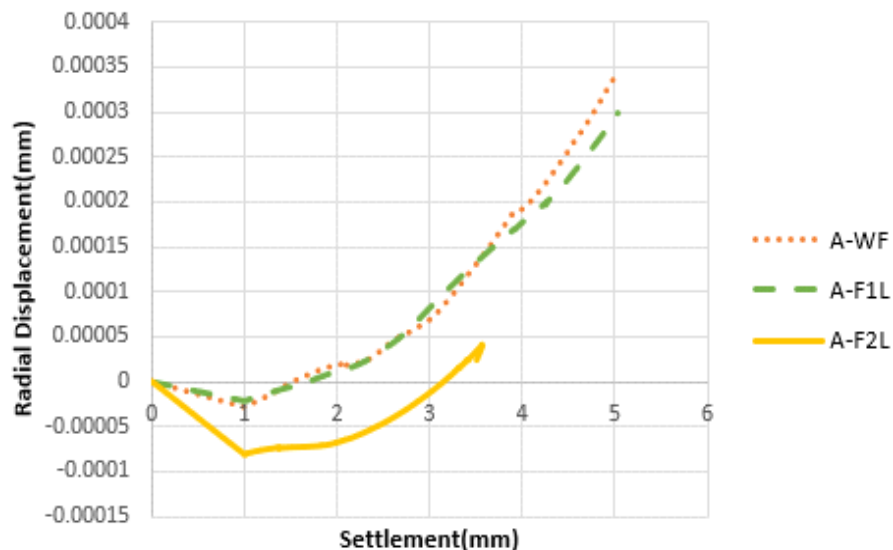


Figure 6. Settlement–radial displacement curves for specimens with 0.3 mm wall thickness under local support settlement

According to Figure 6, strengthening the specimens with CFRP reduces their radial displacement for a given settlement.

4. CONCLUSION

Based on the study conducted and briefly presented in this paper, the following conclusions can be drawn:

- 1- In specimens strengthened with CFRP, both the magnitude and the extent of the deformed region decrease, and the maximum displacement in all directions is reduced.
- 2- By strengthening the specimens and increasing their wall thickness, the equivalent load associated with a given settlement increases, and the target settlement occurs at a higher load level.
- 3- In strengthened specimens, the radial displacement corresponding to a given settlement is reduced.
- 4- The use of CFRP for strengthening cylindrical shells is a highly effective and practical method.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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